

Can the RHIC J/ψ puzzle(s) be settled at LHC?

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Abstract. One observes strong suppression effects for hard probes, e.g. the production of J/ψ or high- p_T particles, in nucleus-nucleus (AA) collisions at RHIC. Surprisingly, the magnitude of the suppression is quite similar to that at SPS. In order to establish whether these features arise due to the presence of a thermalized system of quarks and gluons formed in the course of the collision, one should investigate the impact of suppression mechanisms which do not explicitly involve such a state. We calculate shadowing for gluons in the Glauber-Gribov theory and propose a model invoking a rapidity-dependent absorptive mechanism motivated by energy-momentum conservation effects. Furthermore, final state suppression due to interaction with co-moving matter (hadronic or pre-hadronic) has been shown to describe data at SPS. We extend this model by including the backward reaction channel, i.e. recombination of open charm, which is estimated directly from pp data at RHIC. Strong suppression of charmonium both in pA and AA collisions at LHC is predicted. This is in stark contrast with the predictions of models assuming QGP formation and thermalization of heavy quarks.

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1 Introduction

Charmonium production off nuclei is one of the most promising probes for studying properties of matter created in ultrarelativistic heavy ion collisions. Being a heavy particle, it can be used as a probe of the properties of the medium created in these collisions, such as the intensity of interactions and possible thermalization.

The RHIC era in charmonium physics has brought to light further aspects beyond what was known during the SPS experiments. The gold plated signal of charmonium suppression due to colour screening in a quark-gluon plasma was shown to be a characteristic of models which did not assume such a state and recently the study of charmonium regeneration, or recombination, has become a field of active study. In this sense the results from RHIC establish an important step, bridging the vast energy jump to the future LHC experiments.

The RHIC results on the centrality-dependent nuclear modification factor of charmonium in Au+Au collisions at $\sqrt{s} = 200$ GeV [1] contained two puzzling features. The first was the fact, that the suppression at mid-rapidity coincided with the level of suppression in Pb+Pb collisions at $\sqrt{s} = 17.3$ GeV for the same number of participants [2]. Since the medium produced at RHIC is denser and lives longer than at SPS one would, a priori, expect a stronger suppression with increasing energy. The second puzzling feature was the stronger suppression at forward rapidity than at $y = 0$. Once again, the medium in the central part of the collision is the most dense and from simple arguments we would expect an opposite behaviour than what is seen in the data. Additionally, data on charmonium in d+Au collisions at the same energy revealed a decrease of the suppression due to cold nuclear matter compared to lower energies.

These seemingly puzzling features in the data bring to light two new aspects of charmonium physics in nuclear reactions, namely the role of initial state effects and the role of possible secondary J/ψ production from recombina-

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nation of open charm. At RHIC these effects are visible and important for the detailed description, at LHC their magnitude, especially the gluon shadowing, will be much larger. We argue that only the full description of charmonium dynamics from SPS to LHC energies will shed new light on the underlying physics of dense partonic systems.

2 Baseline: initial state effects

In order to quantify the modifications of charmonium due to the presence of a dense partonic medium, one usually starts from the simpler proton-nucleus (pA) collisions. At least two modifications in the pA case compared to pp are known to come into play. On the one hand, charmonium suppression is seen to scale with L , the traversed path length by the initially formed $c\bar{c}$ pair within the nuclear medium. In the Glauber model, this leads to a suppression factor $\propto \exp(-\rho L \sigma_{abs})$, controlled by the so-called absorptive cross section, σ_{abs} . In p+Pb collisions at $\sqrt{s} = 19$ GeV this cross section was found to be ~ 4.5 mb [3]. On the other hand, the nuclear gluon distribution is modified at high energies, leading to

$$R_g^A \equiv \frac{g^A(x, Q^2)}{Ag^p(x, Q^2)} < 1, \quad (1)$$

at values of Bjorken- $x < 0.1$, called gluon shadowing. Usually one assumes a gluon fusion mechanism for the charmonium production, and therefore this effect is of crucial importance.

Recently, it has been realized that the nuclear suppression of charmonium in pA collision exhibits a non-trivial energy dependence (see e.g. [4,5]) namely, that σ_{abs} is decreasing with energy, $17.3 < \sqrt{s} < 45$ GeV, in contrast to elementary theoretical expectations [6]. At RHIC, the situation is more complex due to the presence of additional gluon shadowing. The absorptive cross section introduced above is replaced by a rapidity-independent $\sigma_{break-up}$ which takes values in the range $\{0.7, 4.5\}$ mb, depending on which shadowing parameterization is chosen [7,8]. This approach seems to be in conflict with the strong x_F -dependence of J/ψ suppression observed in [9,10], although the accessible range of x_F at RHIC is quite limited. In summary, there are still many open questions which seems to lack an explanation within a unified framework.

The observed trends are, in fact, in line with expectations from the Glauber-Gribov theory [11,12]. In this approach the quantity σ_{abs} controls the contribution of a certain set of diagrams valid at low energies, which corresponds to the Glauber model. More involved diagrams become, of course, important at high energies [13]. They correspond to a space-time picture where the initially small projectile evolves into a large fluctuation which can interact coherently with all of the constituents of the target nucleus. This leads to nuclear shadowing. The transition from the former, planar, to the latter, non-planar, regime is governed by a critical energy scale

$$s_M = \frac{M_{c\bar{c}}^2}{x_+} \frac{R_A m_N}{\sqrt{3}}, \quad (2)$$

where $M_{c\bar{c}}$ is the mass and $x_+ = (\sqrt{x_F + 4M_{c\bar{c}}^2/s} + x_F)/2$ is the longitudinal momentum fraction of the heavy system. This transition signals the breakdown of the semiclassical probabilistic picture of longitudinally ordered multiple scattering as one goes to high energies, $s > s_M$. In this scenario, the diagrams that are controlled by σ_{abs} are cancelled in the summation and, instead, shadowing of nuclear partons appear [14].

At finite energies there are also well known corrections due to conservation of energy-momentum [15,11]. These are, of course, most prominent when $x_F \rightarrow 1$, but can also lead to suppression at mid-rapidity.

These features lead us to propose the following model for charmonium suppression at all energies, see [16] for the details. The suppression of charmonium in pA compared to A elementary pp collisions is given by

$$R_{pA}^{c\bar{c}}(x_F, s) = \frac{1}{A} \int d^2b S^{FE}(x_+, b) S^{shad}(x_2, Q^2, b). \quad (3)$$

The finite energy (FE) suppression factor, $S^{FE}(x_+, b)$, is given by [12]

$$S^{FE}(x_+, b) = \begin{cases} \frac{1}{T_A(b)} [1 - \exp(-\tilde{\sigma} T_A(b))] & \text{for } s < s_M \\ T_A(b) \exp(-\tilde{\sigma} T_A(b)/2) & \text{for } s \geq s_M \end{cases} \quad (4)$$

where the nuclear profile function, $T_A(b)$, is normalized to the atomic number, A , and the shadowing correction, $S^{shad}(x_2, Q^2, b)$, for the gluons in the nucleus carrying a momentum fraction x_2 is taken from [17]. Note, that no antishadowing effects are included in this model.

The "generalized" absorptive cross section that enters eq. (4) is a function of x_+ [11,16]

$$\tilde{\sigma}(x_+) = [(1 - \epsilon)\Phi(t_{min}) + \epsilon x_+^\gamma] \sigma_{c\bar{c}}, \quad (5)$$

where $\sigma_{c\bar{c}}$ is the total $c\bar{c} - N$ cross section, $\gamma = 2$ for charmonium [11] and ϵ is a parameter characterizing the amount of longitudinal momentum lost in each rescattering. The "form factor"

$$\Phi(t_{min}) = \exp\{-x_2^c/x_2\}^2\}, \quad (6)$$

where $x_2^c \approx 0.1$ corresponds to the critical energy scale in eq. (2), controls the transition from the planar to the non-planar regime. Note, that in the low-energy limit and at mid-rapidity, where no shadowing corrections exist, $S^{shad} = 1$, the ordinary absorption in this model is given by

$$\tilde{\sigma} \xrightarrow{M_{c\bar{c}}^2/s \sim 1} [(1 - \epsilon) + \epsilon M_{c\bar{c}}^2/s] \sigma_{c\bar{c}}, \quad (7)$$

whereas the Glauber result, without energy-momentum conservation, would be simply $\sigma_{abs} = (1 - \epsilon)\sigma_{c\bar{c}}$. In the high-energy limit at mid-rapidity, on the other hand,

$$\tilde{\sigma} \xrightarrow{s \gg M_{c\bar{c}}^2} 0, \quad (8)$$

so that $S^{FE} = 1$ and the suppression is fully governed by the shadowing corrections. The parameters $\sigma_{c\bar{c}}$ and ϵ have been extracted from low energy data in [16].

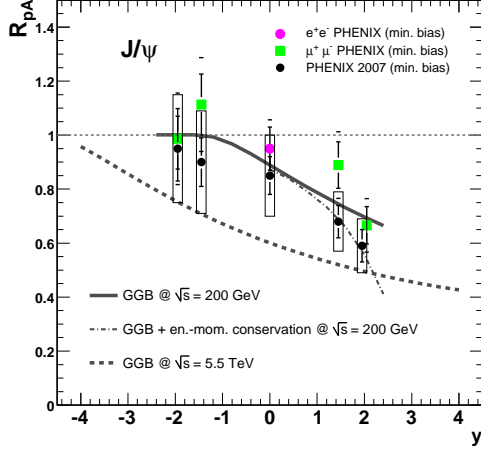


Fig. 1. Rapidity dependence of J/ψ suppression in pA collisions at RHIC and LHC. Data are from [7,8].

In figure 1 we compare our calculations of gluon shadowing [17] (solid curve) and additionally with energy-momentum conservation (dash-dotted) curve to data on J/ψ in $d+Au$ collisions at $\sqrt{s} = 200$ GeV [7,8]. The latter effect becomes important already at $y = 2$. Note, that the same mechanism will also affect the forward yields of charged hadrons at even smaller rapidities.

This constitutes the baseline in the search for the origin of anomalous suppression in high-energy AA collisions. Also, we also plot the predicted J/ψ suppression in $p+Pb$ collisions at LHC (see figure 1).

3 Comover absorption and recombination of charmonium

In the following section we will briefly describe the so-called co-mover model for the case of charmonium secondary interactions. It was originally formulated to explain the anomalous J/ψ suppression in AA collisions at the SPS [18,19,20,21]. Recently, predictions were made for RHIC including only comover dissociation [22].

As previously discussed, the possibility of recombination of $c\bar{c}$ pairs in the dense medium cannot be neglected at RHIC, due to the considerable density of open charm at mid-rapidity. This recombination mechanism was first introduced in [23] neglecting spatial dependencies in the J/ψ and open charm densities. The approach has recently been improved in [24,25] and charmonium recombination has also been considered in statistical hadronization models with charm conservation [26,27]. The dynamics of charmonium recombination and dissociation has also been implemented in various scenarios in Monte-Carlo models (see e.g. [28]).

The recombination mechanism has recently also been included in the co-movers interaction model (CIM) [29]. Assuming a pure longitudinal expansion and boost invariance of the system, the rate equation which includes both

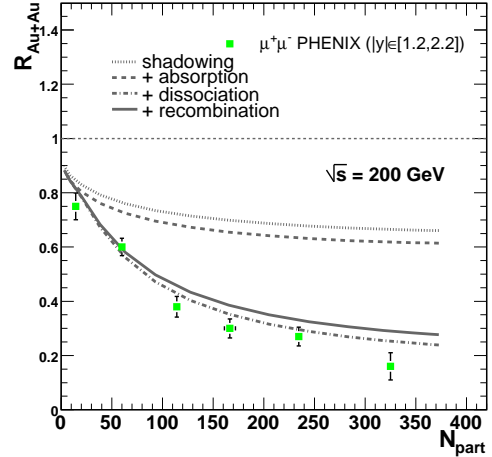
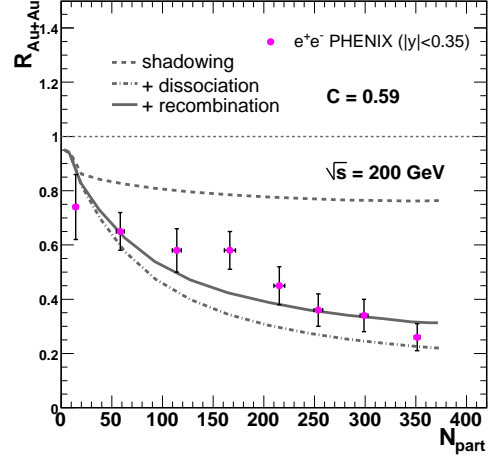


Fig. 2. Results for J/ψ suppression in $Au+Au$ collisions at $\sqrt{s} = 200$ GeV at mid- (upper figure) and forward (lower figure) rapidities. Data are taken from [1].

dissociation and recombination effects for the density of charmonium at a given production point at impact parameter s reads

$$\tau \frac{dN_{J/\psi}(b, s, y)}{d\tau} = -\sigma_{co} \left[N^{co}(b, s, y) N_{J/\psi}(b, s, y) - N_c(b, s, y) N_{\bar{c}}(b, s, y) \right], \quad (9)$$

where N^{co} , $N_{J/\psi}$ and $N_{c(\bar{c})}$ is the density of comovers, J/ψ and open charm, respectively, and σ_{co} is the interaction cross section for both dissociation of charmonium with co-movers and regeneration of J/ψ from $c\bar{c}$ pairs in the system averaged over the momentum distribution of the participants. It is the constant of proportionality for both the dissociation and recombination terms due to detailed balance.

Note, that the quantities that enter the rate equation, eq. (9), are densities of co-moving matter at the same impact parameter as the J/ψ produced in the initial hard scattering. This is quite different from other approaches,

e.g. [23] and also the statistical hadronization models [26, 27], where $c\bar{c}$ pairs in an extensive volume are allowed to recombine. In our case, the system is driven to a local equilibrium, given by

$$N_{J/\psi}(b, s, y) = \frac{N_c(b, s, y) N_{\bar{c}}(b, s, y)}{N^{co}(b, s, y)}. \quad (10)$$

Equation (9) cannot be solved analytically. The suppression factor, i.e. the density of ratio of J/ψ after the full evolution of the medium to the one at some formation time τ_0 , can be approximated by

$$S^{co}(b, s, y) = \exp \left\{ -\sigma_{co} [N^{co}(b, s, y) - C(y) N_{bin}(b, s) S^{shad}(b, s, y)] \right. \\ \left. \times \ln \left[\frac{N^{co}}{N_{pp}(0)} \right] \right\}, \quad (11)$$

where

$$C(y) = \frac{(d\sigma_{pp}^{c\bar{c}}/dy)^2}{\sigma_{pp}^{ND} d\sigma_{pp}^{J/\psi}/dy}. \quad (12)$$

Details of the model can be found in [29]. The quantities in eq. (12) are all related to pp collisions at the corresponding energy and are taken from experiment. Formulated as above, the extension of CIM with inclusion of recombination effects does not involve any additional parameters.

With $\sigma_{co} = 0.65$ mb [19, 20, 21] fixed from experiments at lower energies, we have calculated the suppression of J/ψ in Cu+Cu and Au+Au collisions at $\sqrt{s} = 200$ GeV in [29]. We present results for the Au+Au case for both mid- and forward rapidities in fig. 2. Both the centrality and rapidity dependence are in good agreement with the data.

The latter is due to a combination of stronger initial state effects at forward rapidities and the fact that recombination effects are weaker than at mid-rapidity. In a natural way, the CIM explains both of the observed J/ψ puzzles in AA collisions discussed earlier.

4 J/ψ suppression at LHC

Predictions for LHC energy of $\sqrt{s} = 5.5$ TeV can be readily done assuming that $d\sigma_{c\bar{c}}/dy|_{y=0} \sim 1$ mb and $\sigma_{pp}^{ND} = 59$ mb which corresponds to $C = 2.5$; σ_{co} is kept constant. They are presented in fig. 3.

These predictions are in stark contrast with predictions of the statistical hadronization model [30], which favours a strong enhancement of J/ψ for the most central collisions.

The reason of the discrepancy is the local form of our rate equation: only comovers and open charm produced at the same impact parameter as the initial J/ψ are allowed to interact. On the other hand, models assuming global equilibrium of the produced charm with the medium allow for recombination of $c\bar{c}$ pairs from the whole volume

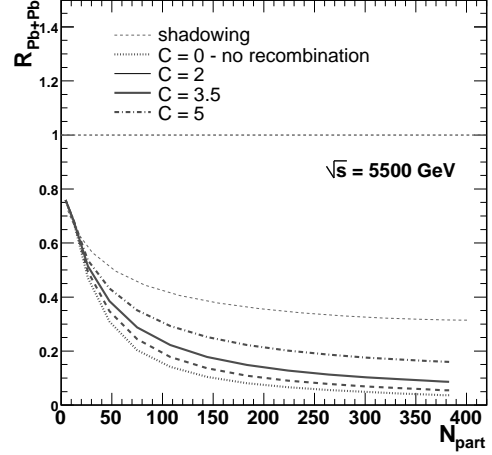


Fig. 3. Prediction for J/ψ suppression in Pb+Pb collisions at mid-rapidity at LHC for different values of the parameter C . The upper line is the suppression due to gluon shadowing.

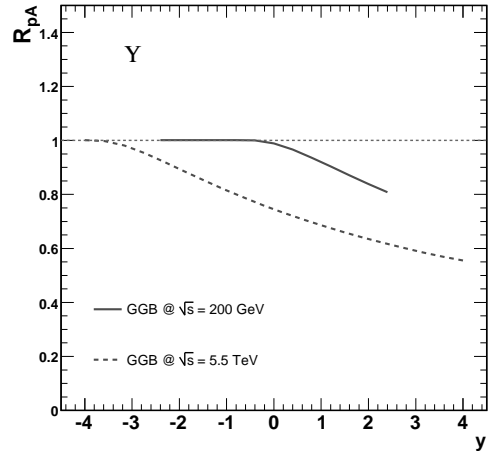


Fig. 4. Suppression of γ at RHIC and LHC.

of the fireball. A recent analysis suggests that the thermal relaxation times of charmed quarks are rather long at RHIC, $\tau_c \sim 5 - 7$ fm/c [31], but the situation is poorly known at LHC. Another point of dispute is the importance of initial state effects, which amount to almost 50% of the suppression in the CIM.

The large lever arm in energy and densities of produced will hopefully help us to understand and disentangle these issues in the future.

5 Suppression of bottomonium at LHC

Finally, we present some results for bottomonium at RHIC and at LHC, where excellent detector capabilities will allow us to look in detail at the Υ family. Since the Υ state is much smaller than charmonium, it may provide a clearer probe of a thermalized system due to its presumably weaker interaction with matter. On the other hand,

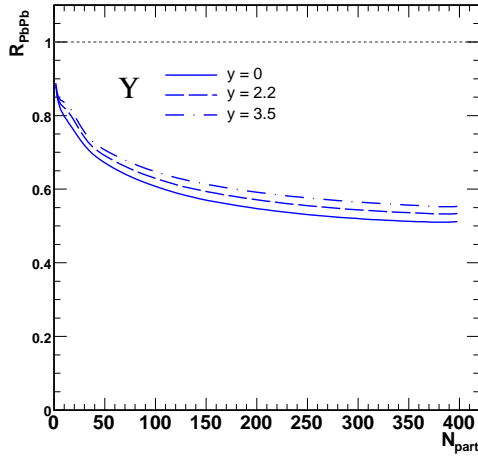


Fig. 5. Centrality dependence of Υ suppression due to initial state effects (gluon shadowing) in Pb+Pb collisions at $\sqrt{s} = 5.5$ TeV.

due to strong binding energy, it may not dissolve at temperatures typical for heavy-ion collisions [32]. Predictions for LHC has previously been presented in [33].

Here, we would only like to discuss the impact of initial state effects on bottomonium production (for a recent discussion of final state medium effects we refer to [34]). The absorptive cross section for Υ is 40-50% smaller than the corresponding cross section for J/ψ and ψ' . Furthermore, energy-momentum conservation mechanisms are pushed to higher x_F due to the large mass of the bottomonium (corresponding to $\gamma \sim 3$ in eq. (5)). We expect therefore negligible nuclear absorption for RHIC and LHC kinematics.

Shadowing for bottomonium in pA collisions is shown in fig. 4 as a function of rapidity at RHIC and LHC energies. Since our model [17] does not contain antishadowing, the predictions for backward and mid-rapidities are uncertain up to the 10% level, but we expect shadowing at forward rapidity at RHIC. At LHC, a large suppression is predicted for $p+Pb$ collisions in most of the kinematics.

The suppression of bottomonium due to gluon shadowing in Pb+Pb collisions at LHC is shown in fig. 5 for several rapidities. The suppression is about 50% from mid-central to central collisions, and would be the same for all members of the Υ family. This establishes the baseline for further calculations of bottomonium dissociation and recombination in the final state.

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